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RESEARCH MEMORANDUM

EXAMINATION OF SMOKE AND CARBON FROM

TURBOJET-ENGINE COMBUSTORS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

Smoke and carbon from turbojet-engine combustors were studied by the methods of electron microscopy, chemical analysis, and X-ray diffraction. The smoke exhausting from a combustor was found to consist of carbon black, agglomerated into soot. The carbon black had been partially burned in its passage through the flame zone. The smoke resulted from the incomplete combustion of the vaporized fuel; it was not the result of the pyrolysis of fuel droplets.

The soft carbon in the dome of the combustor liner was found to consist of carbon black and soot intermixed with indeterminate complexes such as high-boiling fuel ends and partly polymerized and pyrolyzed heavy hydrocarbons.

The hard carbon on the walls of the combustor liner was found to be largely a petroleum coke. The coke was apparently formed by the liquid phase cracking, pyrolysis, and subsequent coking on the liner wall of fuel from the spray nozzle.

INTRODUCTION

The formation of smoke and the deposition of carbon in the combustion chamber are two undesirable features of the combustion process in turbojet engines (reference 1). The smoking and carbon-forming tendencies of a specific turbojet engine could undoubtedly be decreased if the results of a systematic study of design, operational, and fuel parameters were applied. To have a basic knowledge of the origin and mechanism of the formation of smoke and carbon would be desirable, however, before any problem of this kind is undertaken. Such knowledge should make possible a more specific determination of the type of remedial action required for the general case of smoke or carbon formation in any combustion chamber.

In order for the study of the fundamentals of smoke and carbon formation to be applicable to turbojet engines, the study must deal with the formation processes and types of smoke and carbon actually found in

such engines. For example, two methods of smoke formation can be postulated: the smoke might be a result of the pyrolysis of fuel droplets, or it might be a result of the incomplete combustion of the vaporized fuel. The determination of the correct mechanism would indicate whether emphasis should be placed on the fundamental study of the combustion of fuel sprays or of gaseous mixing and diffusion.

This report presents the results of an analysis made at the NACA Lewis laboratory of the smoke and carbon obtained from turbojet-engine combustors. The characteristics of various types of carbon formation and methods of analysis which can be used to distinguish among these various types of fuel residue are discussed. The analytical methods used were electron microscopy, carbon-hydrogen determinations in a combustion train, and X-ray diffraction. Electron micrographs of the various types of residue are presented. Described herein are the structures and probable methods of formation for turbojet smoke and the carbon deposits found on the dome and walls of a turbojet combustor liner.

STRUCTURE OF SMOKE AND CARBON

The smoke from a burning hydrocarbon appears normally as a dark gray or black streak or cloud. If a portion of this smoke is allowed to impinge on a microscope slide it deposits as a structureless film of carbon black. If the flame smokes heavily and the smoke-air mixture is swirled and mixed before collection, the smoke tends to coagulate into small particles of soot. If a smoke mixture of this second type is allowed to settle on a microscope slide and is examined at X100 magnification, the particles of soot are seen to have a flocculent, lace-like structure (fig. 1(a)). When the edge of a soot particle is examined at X1000 magnification, the lace-like structure seems to be made of tiny particles (fig. 1(b)). If the edge of such a soot particle is examined in the electron microscope at X100,000 magnification, the lace-work structure is found to be made up of strings and clusters of roughly spherical particles of a nearly uniform size (fig. 1(c)). The diameters of these spherical particles may vary from 0.01 to 1.0 micron depending on the type of hydrocarbon burned. The particles may cling together by means of electrostatic attraction or may actually be attached to each other by means of necks (reference 2).

X-ray diffraction studies have been made of hydrocarbon smokes and amorphous carbon blacks (references 3 and 4) which reveal that the spherical particles observed in the electron microscope are made up of agglomerates of tiny mesomorphous crystals. These crystals, or crystallites, have major edge dimensions of approximately 20 angstroms. The crystallites are packed together in a random fashion, much like a popcorn ball structure, to form the spherical particle (fig. 1(d)). A chemical analysis of smoke indicates that about 5 percent of the hydrogen

originally in the hydrocarbon remains in the smoke (reference 5). The spherical particles therefore consist almost completely of carbon and are the intermediate structural units of soots, smokes, and carbon blacks. For purposes of identification in this report, these small spherical particles will be called carbon particles.

The atomic structure of the crystallites making up the carbon particles has been determined from an analysis of X-ray diffraction patterns (references 3 to 5). The crystallite consists of several layers of carbon atoms lying in distorted hexagonal crystal lattices. The distortion of the crystal lattice is attributed to the presence of the residual hydrogen mentioned previously (see reference 5). The layers of carbon atoms are parallel to each other and spaced in a fashion characteristic of graphite. However, the planes are not oriented parallel to each other along the other two axes as is the case for graphite. A graphite crystallite might be compared to a deck of playing cards oriented as they are when stored in their box. A smoke crystallite might be compared to the same deck of cards put on a spindle with the edges of the cards turned at random angles to each other.

The X-ray diffraction pattern of smoke consists of two diffuse rings because of the small particle size of the crystallites. The X-ray diffraction pattern of graphite consists of sharp rings (reference 6). A gradual transition from smoke, or carbon black, to graphite can be distinguished in X-ray diffraction analysis by the gradually sharpening images of the ring pattern.

The methods of electron microscopy, chemical analysis for carbon and hydrogen, and X-ray diffraction can therefore be used to differentiate among various types of hydrocarbon residue.

APPARATUS AND PROCEDURE

Collection of Samples

The sample of smoke from the turbojet-engine combustor was obtained by bleeding combustor exhaust gases through a heat exchanger and then through a sintered glass filter funnel attached to a vacuum line. The funnel was loosely packed with glass wool which formed collecting supports for the smoke. The smoke was then shaken from the glass wool and scraped from the sides of the funnel. The smoke sampling probe remained substantially clean inside and out, and the smoke sample was assumed to be representative.

The carbon samples were obtained with a fuel different from that used for the combustor smoke tests (table I). The carbon samples were removed from both the dome and the walls of the combustor liner. Stalactites of hard carbon were broken from the liner with tweezers, and

flakes of soft carbon were lifted from the dome with a spatula. This care was taken to assure representative samples and structures from the two regions.

A sample of the turbojet-engine fuel used in these combustor smoke studies was burned in a wick lamp with the flame adjusted high enough to smoke, and the smoke was collected on a cooled brass plate. The smoke was scraped from the brass plate with a glass slide.

Electron Microscopy of Samples

The combustor carbons and smokes were individually dispersed on a glass slide with a glass rod. Each dispersed sample was then sprinkled over the standard 1/8-inch specimen screen used in the electron microscope. Enough sample adhered to the mesh screen for adequate examination at high magnification.

Several specimens of each carbon and smoke sample were examined in the microscope. A number of fields of view in each sample were studied to determine the structure most characteristic of the sample. Several electron micrographs of representative structures were taken for each carbon and smoke sample. The magnification of the pictures was determined by means of an electron micrograph of a collodion replica of a diffraction grating with a known line spacing.

Chemical Analysis of Samples

A standard carbon-hydrogen combustion train was used to determine the hydrogen-carbon ratios of the original fuels used and of the carbon and smoke studied. The carbon and smoke to be examined were ground to a powder in a mortar and dried at 120° C for several hours to eliminate moisture. The hydrogen-carbon ratios were determined in the combustion train in the usual manner.

X-Ray Analysis of Samples

The X-ray diffraction analysis was made with a commercial X-ray diffraction unit equipped with Debye-Scherrer cameras. No binders or supporting films were used to mount the carbon and smoke samples because the patterns of these materials would obscure the carbon pattern. The liner carbon was self-supporting. The other smokes and carbons mentioned previously were pressed into wafers and held in place over 1/8-inch apertures with cellulose tape straps located outside the beam area.

RESULTS AND DISCUSSION

Nature of Combustor Smoke

An electron micrograph of smoke from a turbojet-engine fuel burning in a wick lamp is shown in figure 2(a). Figure 2(b) is an electron micrograph of smoke from a combustor burning the same turbojet-engine fuel. In this figure can be seen a few of the carbon particles shown in figure 2(a). However, the majority of the particles are small and irregular, as if they had been partially consumed in the flame. Studies of carbon combustion in Bunsen burners indicate that it is a process requiring an appreciable length of time to proceed to completion. The carbon is transformed to carbon monoxide which then burns to carbon dioxide in the outer cone (references 7 and 8). Studies of smoke burning in flames indicate that the complete conversion of the carbon in the smoke to gaseous products proceeds at a rate that is controlled by the amount of oxygen in the initial mixture and also by that diffusing into the outer cone. Lean flames therefore burn smoke in a compact mantle around the reaction zone, whereas rich flames burn smoke as a large brush flame (reference 9). Thus, in a turbulent flame of a nonuniform gas mixture such as exists in a combustor, the smoke could be partially consumed and then quenched to give the small ragged carbon particles shown in figure 2(b).

The hydrogen-carbon ratios of the wick lamp smoke and the smoke from the combustor, burning the same fuel, were identical at 0.008 (table II). The original fuel hydrogen-carbon ratio was 0.170, as shown in table I. The smoke therefore contains about 5 percent of the hydrogen originally contained in the fuel as has been found by other workers (reference 5).

The soft consistency of the smoke scraped from the collecting funnel, its appearance at high magnification, and its hydrogen-carbon ratio all indicated that combustor smoke was carbon black agglomerated into soot particles. There was no evidence of large particles of tarry material, or brittle cokes such as would result from the pyrolysis of a liquid hydrocarbon fuel droplet. The carbon particles in figure 2(a) are only one ten-thousandth the size of the smallest pyrolyzed fuel droplet shown in reference 10. Thus, there is little doubt that combustor smoke consists of carbon black agglomerated into soot, as distinct from fuel droplets pyrolyzed in the hot flame zone.

Nature of Combustor Liner Carbon Deposits

Figure 2(c) is an electron micrograph of soft carbon scraped from the dome of a combustor burning an aromatic fuel blend listed in table I. The soft carbon appears to consist of densely packed carbon particles imbedded in a matrix, and the hydrogen-carbon ratio of 0.025 indicates that an appreciable fraction of hydrogen still remains in the material.

The material is firm but easily pulverized. Residual high-boiling fuel ends and partly polymerized products soaked into the carbon black and soot which collects on the dome may account for the consistency, structure, and high hydrogen content of this soot-like residue.

Figure 2(d) is an electron micrograph of pulverized particles of hard carbon picked from the combustor liner wall. This material was hard, vitreous, and brittle. The examples shown in figure 2(d) are particles resulting from grinding the combustor-liner carbon on a glass plate with a glass rod. The samples contained traces of smoke on their edges but were largely of the nature shown. This structure appears to be much different from that of the other smoke and carbon samples. However, X-ray diffraction photographs of this hard carbon and smoke both exhibited the diffuse rings characteristic of small particles and smoke. The similarity indicated that no appreciable change to graphite had occurred in the material. The relatively high hydrogen-carbon ratio of 0.018 suggests the presence of pyrolyzed products, such as petroleum cokes.

Studies of petroleum coke have indicated that the coke consists of tiny mesomorphous crystallites of carbon surrounded by organic compounds of high molecular weight (reference 11). The crystallites, very similar in structure to those in the carbon particles of smoke, should give the same X-ray pattern found in the hard combustor-liner carbon. The ultimate analysis of residues from petroleum heated in a furnace to 800° C (1470° F) for 2 hours or more gives a resultant hydrogen and carbon percentage ratio very nearly that found in the hard combustor-liner carbon. This similarity can be seen in table II of this report. Thus, it would appear that the hard carbon on the combustor liner is a petroleum coke resulting from liquid phase cracking of the fuel. The residue builds up and cokes in the heat generated during the operation of the combustor. This conclusion is confirmed by the work cited in reference 10, where liquid fuel droplets heated in a furnace polymerized into a tarry material which subsequently coked.

CONCLUSIONS

Turbojet-engine combustors have been found to form similar types of smoke and carbon with a variety of fuels. Typical smoke and carbon samples from a turbojet-engine combustor have been analyzed to determine their structural forms and probable methods of formation. The results of these analyses lead to the following conclusions:

1. The smoke exhausting from a combustor consists of carbon black and soot, partially consumed during its passage through the flame zone. The material results from the incomplete combustion of the vaporized fuel; it is not the result of the pyrolysis of fuel droplets.

2. The soft carbon found in the dome of the combustor consists of carbon black and soot intermixed with indeterminate complexes such as high-boiling fuel ends and partly polymerized heavy hydrocarbons.

3. The hard carbon found on the liner of the combustor is largely a petroleum coke resulting from the liquid phase cracking, subsequent pyrolysis, and final coking of the fuel from the spray nozzle as it impinges on the hot liner wall.

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TABLE I - CHARACTERISTICS OF FUELS IN TURBOJET-ENGINE

COMBUSTOR SMOKE AND CARBON TESTS

Fuel property	Aromatic fuel blend used for carbon tests (NACA fuel 49-224)	Jet-engine fuel used for smoke tests (NACA fuel 52-53)
A.S.T.M. distillation, °F		
Percentage evaporated		
0	335	136
5	360	183
10	364	200
20	374	225
30	383	244
40	394	263
50	407	278
60	423	301
70	442	321
80	472	347
90	502	400
Final boiling point	702	498
Residue, percent	0.9	1.2
Loss, percent	0.1	0.7
Specific gravity, 60° F/60° F	0.911	0.757
Gravity, °A.P.I.	23.8	55.4
Hydrogen-carbon ratio	0.108	0.170
Net heat, Btu/lb	18,700	18,200
Bromine number	5	------
Refractive index	1.5987	1.4206
Aromatics, percent by volume (D875-46T)	87.0	8.5

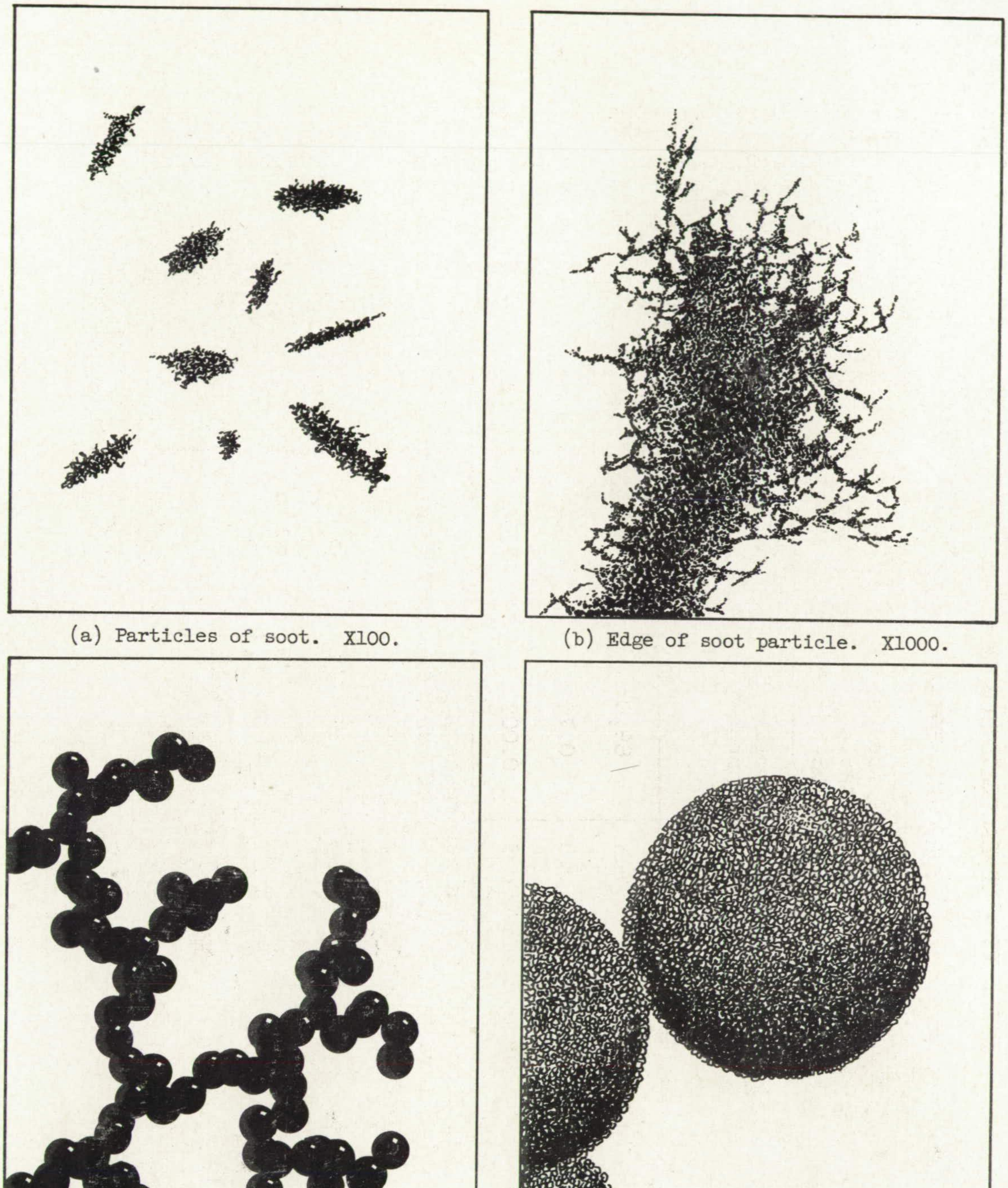
TABLE II - CHARACTERISTICS OF SMOKE AND CARBON FROM

TURBOJET-ENGINE COMBUSTORS

Fuel property	Jet-engine fuel used for smoke tests (NACA fuel 52-53)		Aromatic fuel blend used for carbon tests (NACA fuel 49-224)		Petroleum refining residue[a]
	Smoke, wick lamp	Smoke, combustor	Soft carbon, dome	Hard carbon, liner	Coked at 800° C for 120 minutes
Carbon, percent	96.2	89.0[b]	80.0	92.4	93.3
Hydrogen, percent	0.8	0.70[b]	2.0	1.6	1.9
Hydrogen-carbon ratio	0.008	0.008	0.025	0.018	0.020

[a]Taken from table II in reference 11.

[b]Over-all values low because of contamination by glass wool residues when weighed.



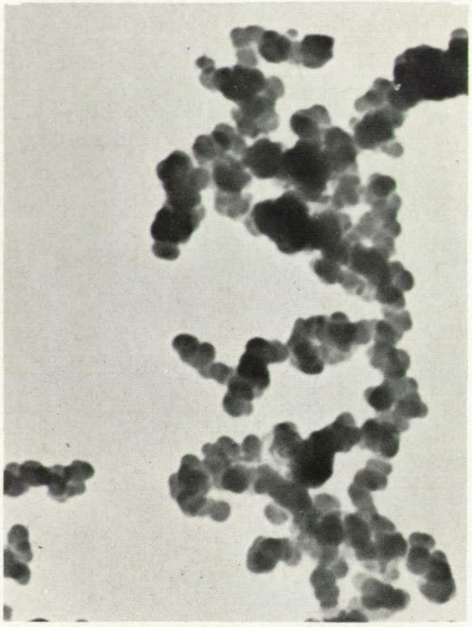
(a) Particles of soot. X100.

(b) Edge of soot particle. X1000.

(c) Edge of soot particle showing chain-like structure of carbon particles. X100,000.

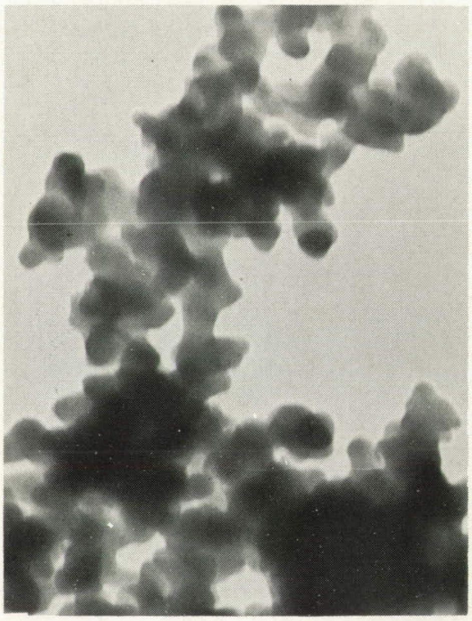
(d) Nature of packed crystallite structure making up carbon particle. X1,000,000.

Figure 1. - Diagrammatic sketches of appearance of carbon black and soot at various magnifications.



(a) Wick lamp smoke of jet-engine fuel. H/C, 0.008.

(b) Smoke collected from exhaust of combustor. H/C, 0.008.



(c) Edge of flake of soft carbon from dome of combustor. H/C, 0.025.

(d) Flakes of pulverized hard carbon from liner of combustor. H/C, 0.018.

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Figure 2. - Electron micrographs of various carbon structures associated with smoke and carbon in jet-engine combustors. X50,000.